

# MEASURING RESEARCH PROGRESS IN PHOTOVOLTAICS

JET PROPULSION LABORATORY

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## Role of PA&I

SUPPORTING THE DECISION-MAKING PROCESS

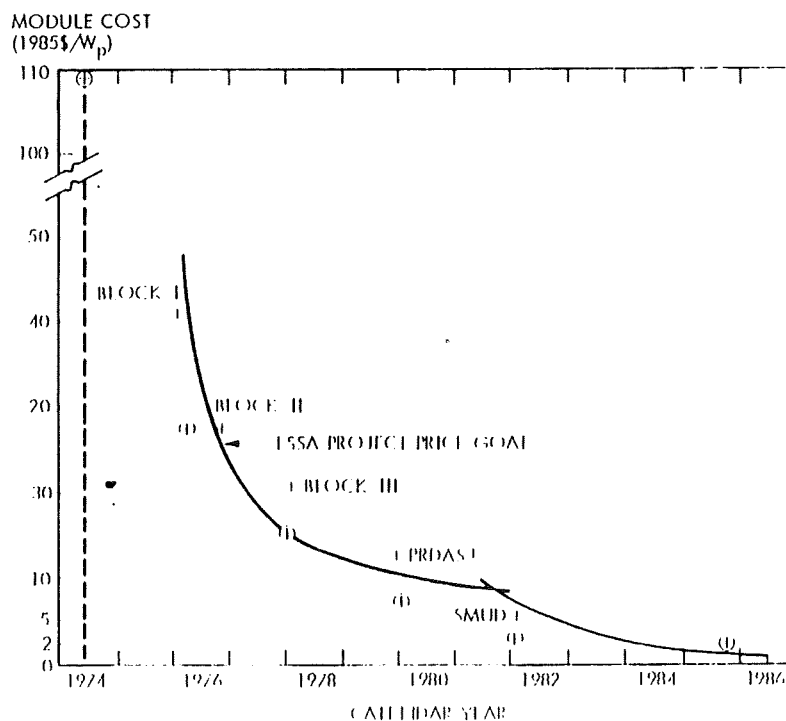
PREPARATION OF PLANS FOR PROJECT DIRECTION

SETTING GOALS FOR PROJECT ACTIVITIES

MEASURING PROGRESS WITHIN THE PROJECT

DEVELOPMENT AND MAINTENANCE OF ANALYTICAL MODELS

## Module Cost Versus Time



## Original Goals of FSA Project

## MODULE PERFORMANCE:

50¢/Wp (1974 DOLLARS)

10% MODULE EFFICIENCY

20 YEAR LIFETIME

26¢/kWh (1985 DOLLARS)

Costs Involved in the Use of State-of-the-Art  
Czochralski Silicon Technology

PROCESS	1985\$
SILICON MATERIAL	0.390
INGOT GROWTH	0.368
INGOT SAWING	0.304
CELL FABRICATION	0.208
MODULE ASSEMBLY	0.179
<b>TOTAL COST (1985\$)</b>	<b>\$1.45/Wp</b>
<b>ENERGY COST (Using Baseline Parameters of the National PV Program)</b>	<b>\$0.275/kWh</b>

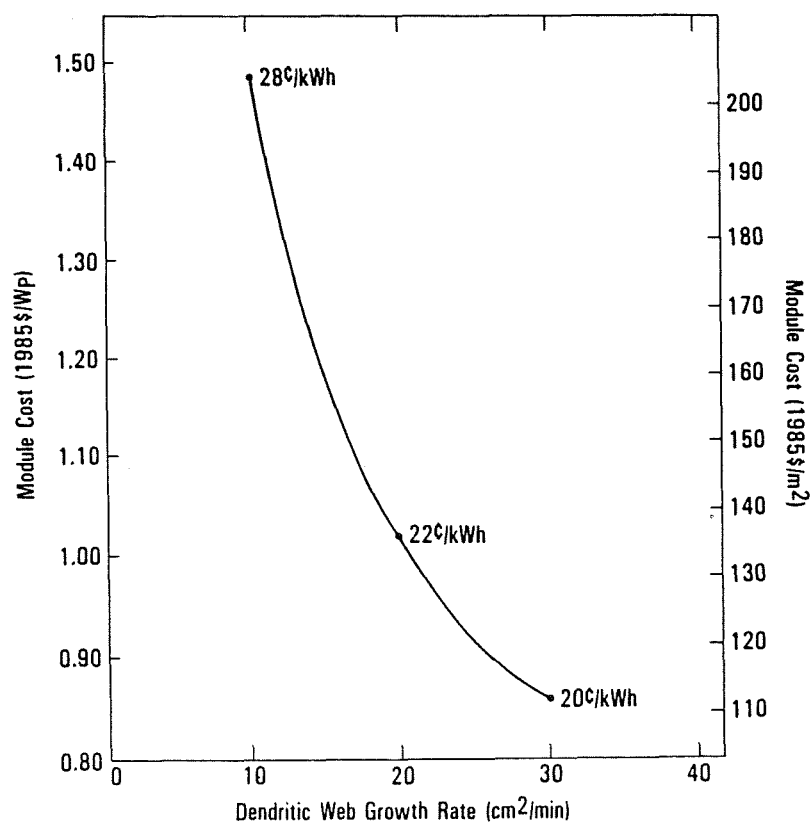
## Assumptions Made in Arriving at Costs Involving Czochralski Silicon

FACTORY SIZE	25 MWp/yr
YEAR OF PRODUCTION	1988
SILICON COST, 1985\$/kg	\$43/kg
CRYSTALLIZATION RATE	1.5 kg/hr (Cz)
INGOT DIAMETER	5 in.
SAWING SLICE + KERF	19 mil
SAWING BLADE PLUNGE RATE	2.0 in./min
SAWING YIELD	95%
CELL SIZE	9.83 x 9.83 cm MODIFIED SQUARE
AREA PER CELL	94.6 cm <sup>2</sup>
PACKING FACTOR	91.4%
MODULE SIZE	122 cm x 61 cm (4 ft x 2 ft)
MODULE POWER	101 Wp
ENCAPSULATED CELL EFFICIENCY	14.8%
MODULE EFFICIENCY, STC	13.5%

## Costs Involved in the Use of Dendritic Web Technology (Projection)

PROCESS	1985\$
SILICON MATERIAL	0.153
WEB GROWTH	0.341
CELL FORMATION	0.119
METALLIZATION	0.162
MODULE ASSEMBLY	0.244
<b>TOTAL COST (1985\$)</b>	<b>\$1.02/W<sub>p</sub></b>
<b>ENERGY COST (Using Baseline Parameters of the National PV Program)</b>	<b>\$0.220/kWh</b>

## Module Cost Versus Dendritic Web Growth Rate



## National Research Program Goals

REVISED SINCE BEGINNING OF PROJECT

SLOWER INCREASES IN CONVENTIONAL ENERGY COST  
HIGHER BALANCE OF SYSTEM COST

PRESENT PROGRAM GOALS

17.1¢/KWH (1985 DOLLARS) FOR LIFECYCLE ENERGY COST

## SAMICS Methodology

ESTIMATES MODULE PRODUCTION COSTS

COSTS DEVELOPED FROM INDIVIDUAL PROCESS DESCRIPTIONS

BASED ON COMPANY DESIGNED SPECIFICALLY FOR MODULE PRODUCTION

METHODOLOGY ASSURES COMPARABILITY OF FINDINGS

## Annual Cost for Each Process Step in the Production of Solar Cell Modules (in 1975 \$/W<sub>p</sub>)

	VALUE ADDED	CAPITAL COSTS	DIRECT LABOR	MATERIALS & SUPPLIES	UTILITIES	INDIRECT EXPENSES	YIELD
SILICON PREP*	0.043			0.0434			
SHEET FAB	0.145	0.0630	0.0312	0.0140	0.0049	0.0320	0.800
P + BACK	0.002	0.0010	0.0004	0.0002	0.0000	0.0005	0.998
ETCH	0.010	0.0036	0.0018	0.0033	0.0000	0.0018	0.994
ION IMPLANT	0.012	0.0067	0.0018	0.0000	0.0003	0.0032	0.998
PULSE ANNEAL	0.006	0.0038	0.0004	0.0000	0.0003	0.0011	0.992
BACK METAL	0.036	0.0108	0.0013	0.0206	0.0005	0.0030	0.980
FRONT METAL	0.036	0.0111	0.0013	0.0202	0.0005	0.0030	0.980
AR COAT	0.009	0.0038	0.0018	0.0014	0.0002	0.0016	0.990
INTERCON	0.033	0.0104	0.0040	0.0135	0.0000	0.0054	0.995
ENCAPSULATE & ASSEMBLE	0.130	0.0368	0.0062	0.0750	0.0001	0.0120	0.999
TEST	0.001	0.0003	0.0002	0.0000	0.0000	0.0002	0.980
PACKAGE	0.001	0.0002	0.0001	0.0002	0.0000	0.0001	0.9999
TOTAL	0.464	0.1515	0.0505	0.1916	0.0068	0.0639	-

\*BASED ON 10 \$/KG SILICON

## SAMIS Personal Computer

### SAMIS

COMPLETE COST STRUCTURE SIMULATION  
PROVIDES DETAILED REPORTS

### SAMPEG

QUICK PROCESS COST ESTIMATES  
COSTS SUMMARIZED BY MAJOR CATEGORIES

### IPEG

RAPID SENSITIVITY STUDIES  
ANALYZE IMPACT OF CHANGES IN FINANCIAL PARAMETERS

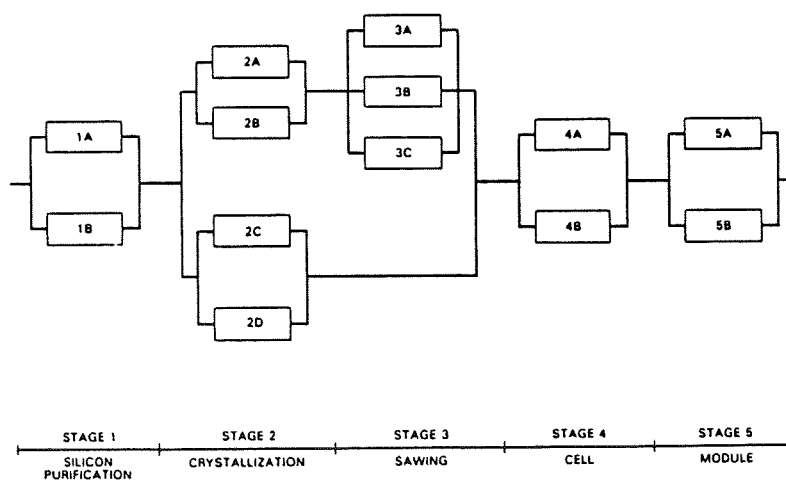
## SIMRAND Methodology

EVALUATION OF COMPLEX R&D DECISIONS

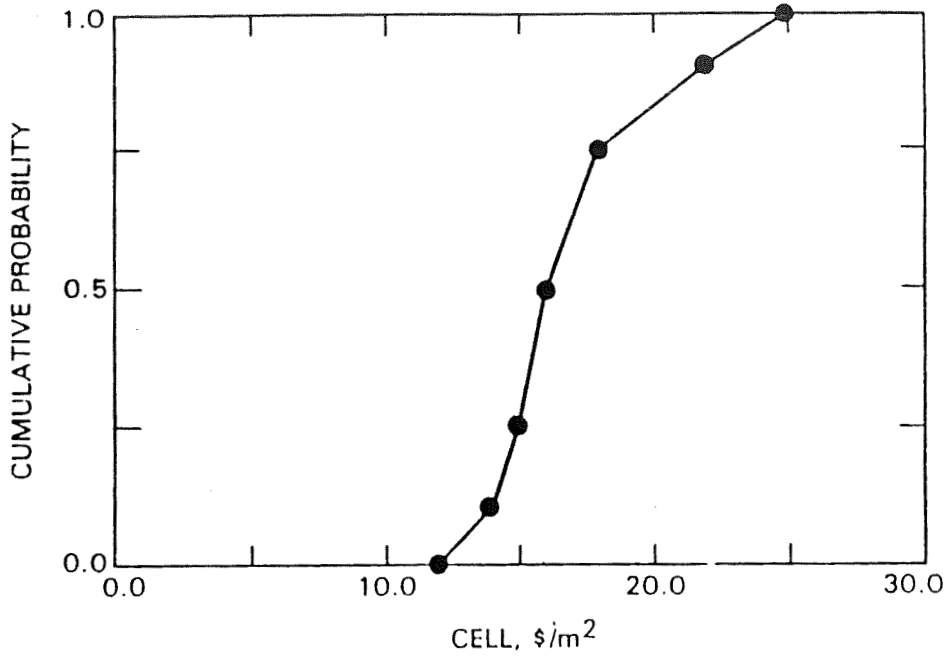
SIMULTANEOUS CONSIDERATION OF SEVERAL PATHS OF ACTION

ELEMENTS OF EACH PATH CAN BE DESCRIBED AS UNCERTAIN

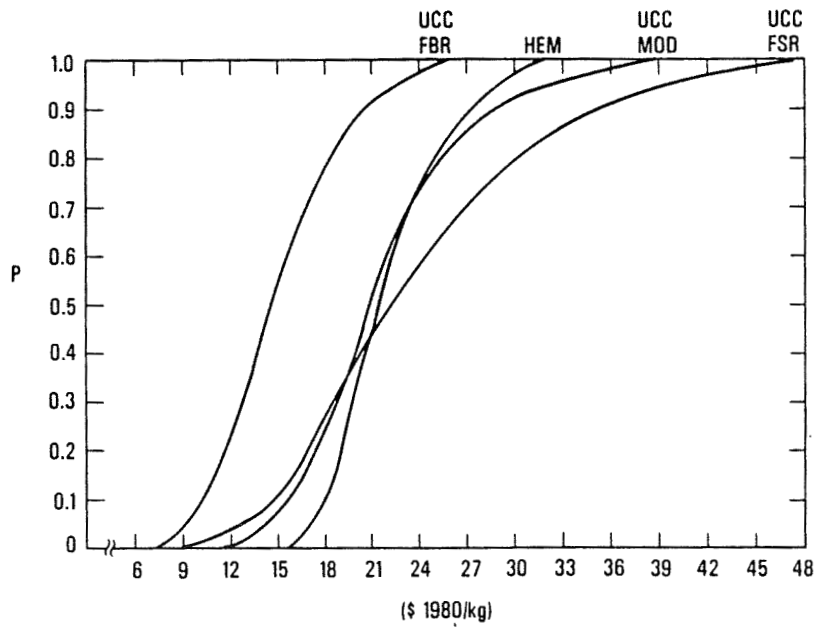
### Task Network for Solar-Cell Module Production (SIMRAND)



Cumulative Probability Versus Solar Cell Cost



Comparison of Cumulative Probability Versus Cost for Various Ways to Produce Silicon



# MODULE AND RELIABILITY TECHNOLOGY

## LCP Methodology

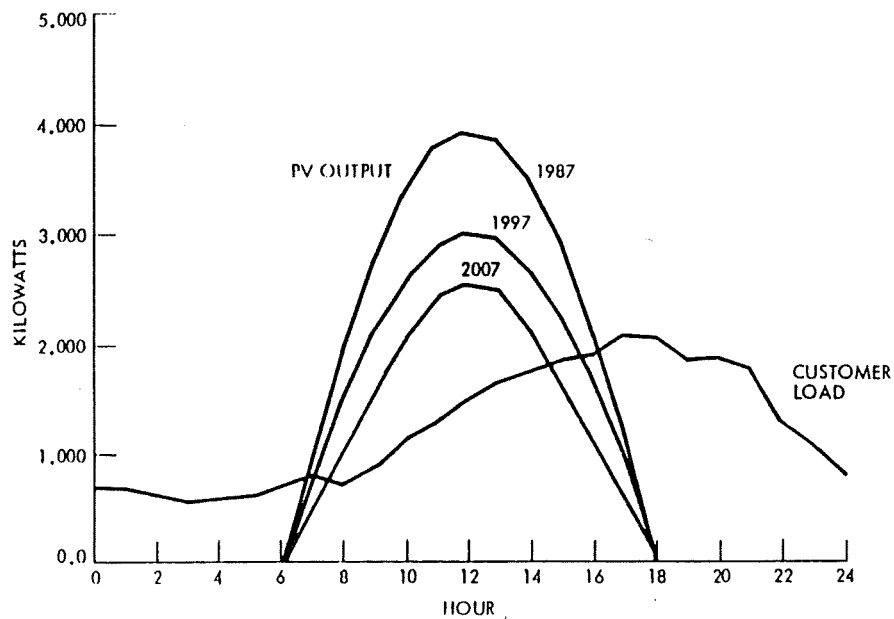
SIMULATES LIFETIME PERFORMANCE OF PV SYSTEM

ESTIMATES SYSTEM OUTPUT, REVENUES AND COSTS

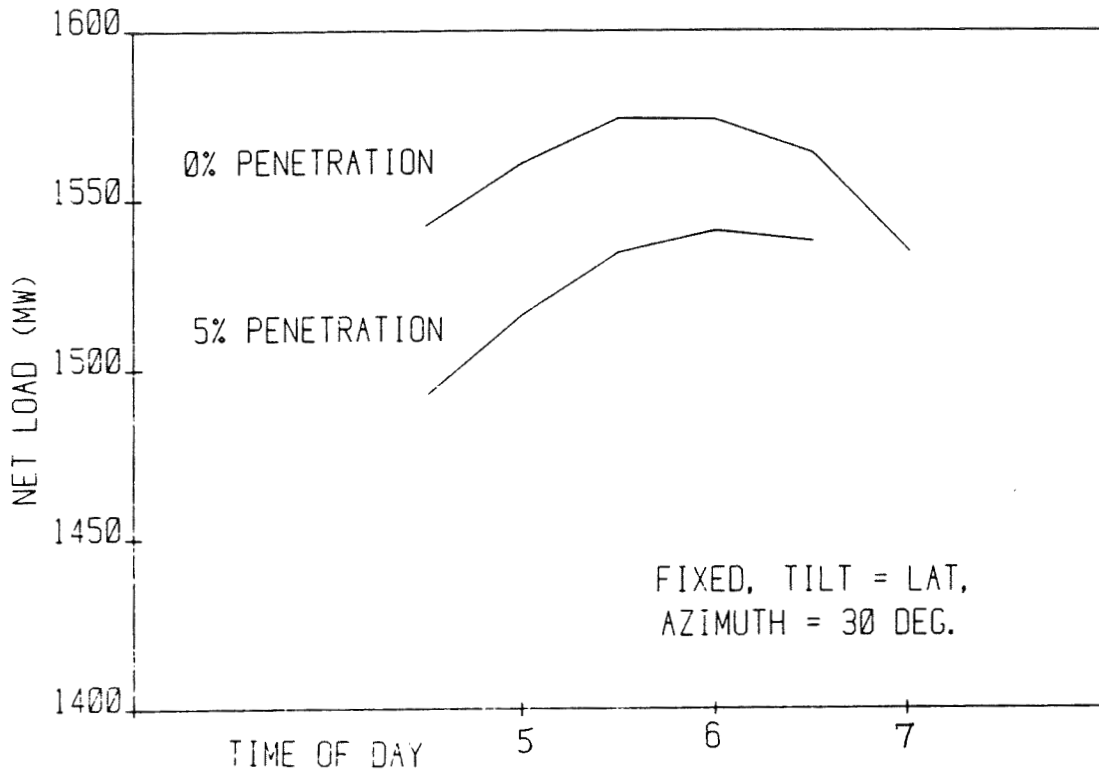
MODELS LOCATION SPECIFIC ENVIRONMENT

APPLICABLE TO UTILITY, RESIDENTIAL OR COMMERCIAL  
INSTALLATIONS

## LCP Simulation



SMUD Net Load Versus Time of Day  
(0 and 5% Penetration on a July Peak Day)



PVARRAY Methodology

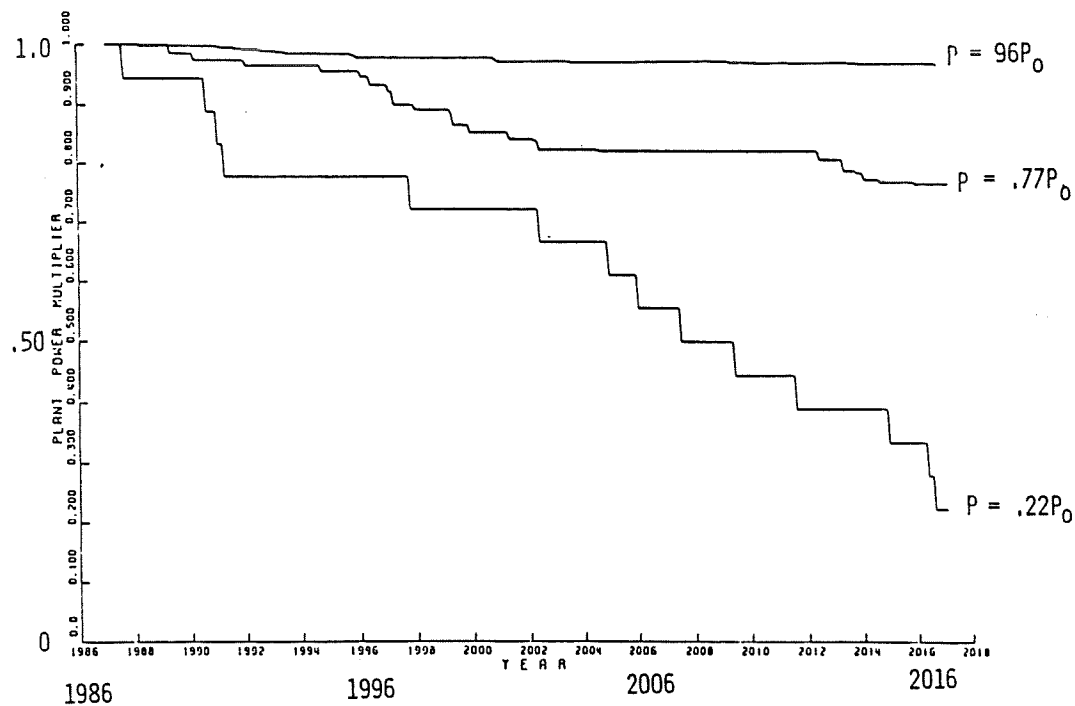
USED TO OPTIMIZE ARRAY DESIGN

SELECT DIODE PLACEMENT

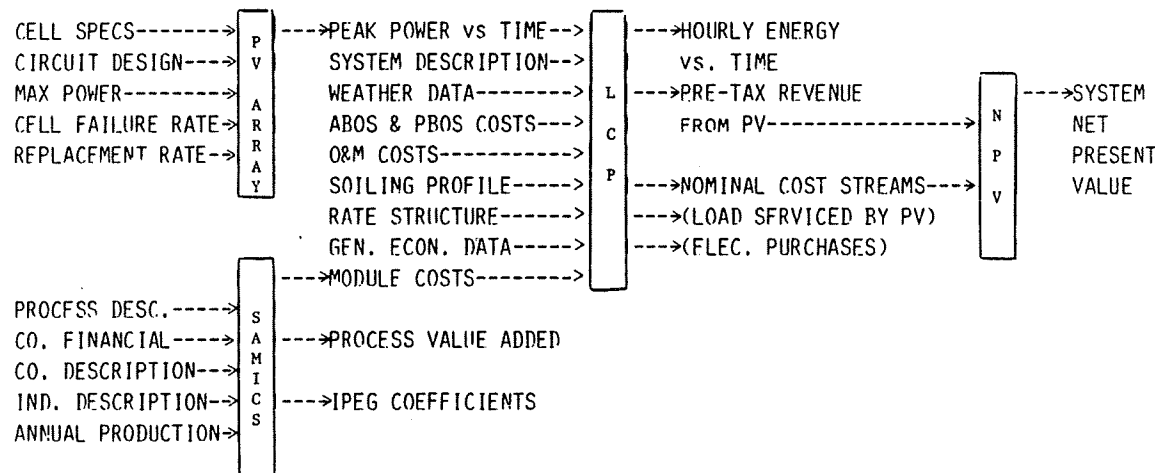
COMPARE ALTERNATE MODULE REPLACEMENT STRATEGIES



Fraction of Array Power Versus Time  
(Cell Failure Rate =  $1 \times 10^{-4}$ /year)



Economic Evaluation Methodology for PV Array Design



SAMICS: SOLAR ARRAY MANUFACTURING INDUSTRY COSTING STANDARDS  
LCP: LIFETIME COST AND PERFORMANCE MODEL

# RELIABILITY PHYSICS

Edward Cuddihy, Chairman

This session consisted of eight presentations on reliability physics.

R. Liang, of JPL, reported that there have been observations of cracks forming in Tedlar back cover films on PV modules mounted outdoors in the natural environment. The cracks appear to approximate reasonable straight lines and, in general, are parallel to each other. It is implied that the directionality of these cracks may be in some way related to film orientation. Preliminary results from JPL studies investigating the causes of these cracks indicate that Tedlar does not become brittle on aging. It was speculated that perhaps compounding ingredients employed in EVA may migrate into the Tedlar film, thus causing a potential for chemical effects. This will be investigated.

On another topic, an experimental technique called "Flash Electron Spin Resonance (ESR)" was described which offers the promise of a quick method for identifying upper temperature limits for accelerated testing of module encapsulation materials.

The presentation by C. Gonzalez, of JPL, described a new, combined environmental aging chamber that was developed at JPL. The chamber has an ultraviolet (UV) light source that can be varied between 1 to 2 suns, temperature control from -40 to +175°C, and adjustable relative humidity. Results from two initial aging experiments (Tedlar and amorphous silicon solar cells) were presented.

J. Guillet reported that the University of Toronto is developing a computer program to simulate the photothermal degradation of materials exposed to terrestrial weathering environments. Input parameters would include the solar spectrum, the daily levels and variations of temperature and relative humidity, and materials such as EVA. A brief description of the program, its operating principles, and how it works was initially described. After that, the presentation focused on the recent work of simulating aging in a normal, terrestrial day-night cycle. This is significant, as almost all accelerated aging schemes maintain a constant light illumination without a dark cycle, and this may be a critical factor not included in acceleration aging schemes. For outdoor aging, the computer model is indicating that the night dark cycle has a dramatic influence on the chemistry of photothermal degradation, and hints that a dark cycle may be needed in accelerated aging schemes.

E. Plueddemann reported that Dow Corning is developing the primers employed in bonding together the various material interfaces in a PV module (such as EVA to glass, for example). The Dow Corning approach develops interfacial adhesion by generating actual chemical bonds between the various materials being bonded together. Dr. Plueddemann described the current status of this program, and the progress toward developing two general purpose primers for EVA, one for glass and metals, and another for plastic films.

J. Boerio reported that the University of Cincinnati is studying the aging behavior of chemically bonded interfaces between metals and pollutants, such as EVA, using the Dow Corning primer systems. As part of this study, it

## RELIABILITY PHYSICS

has been observed that the primers seem to function as anticorrosion agents on metal surfaces. Dr. Boerio has been able to demonstrate that EVA, and the A-11861 EVA/glass primer will stop corrosion of the aluminum used on the back surfaces of crystalline silicon solar cells. However, this same treatment does not seem to work for the aluminum on the back surfaces of amorphous silicon solar cells. This is being investigated.

G. Mon reported that leakage currents are being experimentally measured by JPL in PV modules undergoing natural aging outdoors, and in PV modules undergoing accelerated aging in laboratory environmental chambers. The intent is to identify the significant contributors to module leakage currents, with a long-term goal to develop corrective technologies to reduce or stop module leakage currents. For outdoor aging in general, module leakage current is relatively insensitive to temperature fluctuations, but is very sensitive to moisture effects such as dew, precipitation, and fluctuations in relative humidity. Comparing EVA and polyvinyl butyral (PVB), module leakage currents are much higher in PVB as compared to EVA for all environmental conditions investigated. Leakage currents proceed in series along two paths, bulk conduction followed by interfacial (surfaces) conduction. It is being experimentally observed that leakage current is limited by bulk conduction in EVA modules, but that bulk conduction and interfacial conduction is about the same in PVB modules.

A theoretical modeling of leakage current in EVA and PVB modules is being developed and was described by A. Wen, of JPL. The modeling effort and the experimental effort, described by G. Mon, are two parts of a comprehensive study. The modeling effort derives mathematical relationships for the bulk and surface conductivities of EVA and PVB, the surface conductivities of glass and polymer films, and the interfacial conductivity between glass, polymer films, and the EVA and PVB pottants, all as functions of environmental parameters (temperature, RH, etc.). Some results from the modeling indicate that for glass/EVA, the glass surface controls the interfacial conductivity, although EVA bulk conductivity controls total leakage current. For PVB/glass, the interface conductivity controls leakage currents for RH less than 40 to 50%, but PVB bulk conductivity controls leakage current above 50% RH. This modeling work is continuing.

J. Orehotzky, of Wilkes College, reported that the interface between plastic film back covers and EVA or PVB in PV modules can influence water permeation, and electrical properties of the composite such as leakage current and dielectric constant. The interface can either be of two dissimilar materials in physical contact with no intermixing, or the interface can constitute a thin zone which is an interphase of the two materials having a gradient composition from one material to the other. The former condition is described as a "discrete interface," and Professor Orehotzky was able to develop a discrete interface model to predict water permeation, dielectric strength, and leakage currents for EVA, EMA, and PVB coupled to Tedlar and Mylar films. At this PIM, he compared experimental data with predicted data, and speculated that, in general, EVA and EMA form discrete interfaces, whereas PVB tends to form an interface with an interphase. This developing theory is intended to explain the deviations from expectations for some combinations of materials, on the basis that the properties of the gradient composition interphase controls the interface. His work continues to develop an interphase model for property prediction.

## RELIABILITY PHYSICS

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